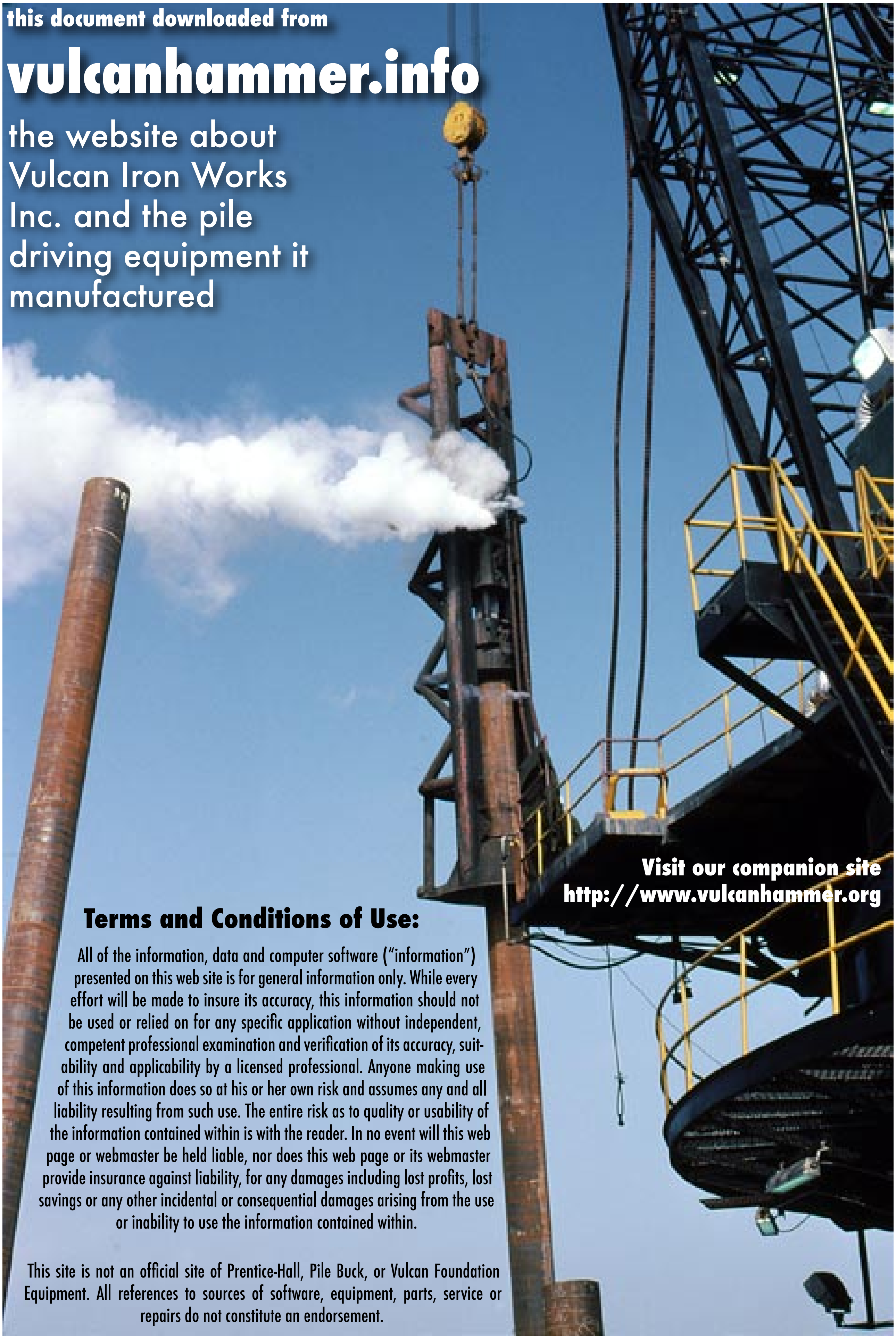

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Ground vibrations caused by pile installation

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Ground vibrations caused by pile installation

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ABSTRACT: The installation of steel sheet or bearing piles by impact hammer or by vibrodriver transmits energy into the ground which can be observed at the surrounding ground surface as transient or periodic vibration. The vibrations may be disturbing to neighbours, and may pose a risk of damage to nearby structures and buried services. Within an extensive programme, ground vibrations have been measured on a large number of piling sites throughout England and Scotland. Vibration components in the radial, transverse and vertical directions at five stations were recorded simultaneously to allow time-based (true) vector resolution, and detailed study of attenuation. Several observations have been deduced directly from the data, but because of the large quantity of data covering different types of hammer, pile and ground, a data base has been constructed.

Estimation of probable vibrations in a given situation can be made by reference to similar case studies extracted from the data base. An expert system for estimation of vibrations has also been developed.

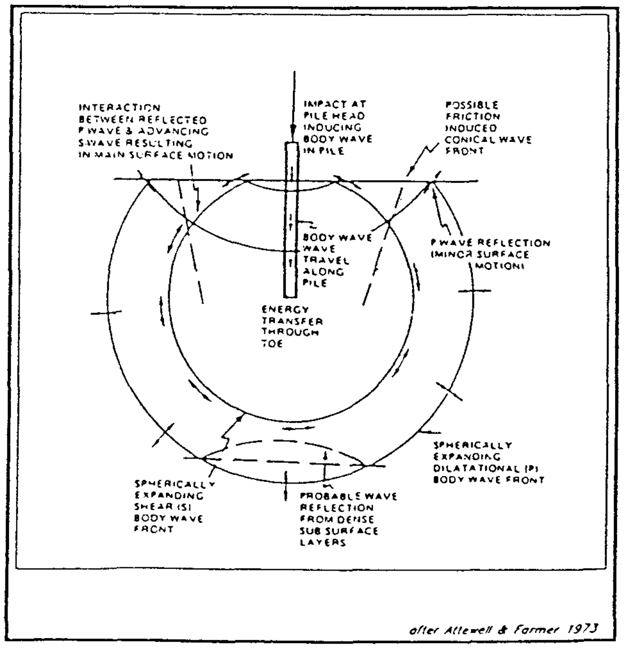
From the many records, covering a range of combinations of soil types, hammers and pile sections, it is shown that vibrations attenuate fairly rapidly to below levels at which minor structural damage is likely. However, the human frame is so sensitive to vibration that annoyance may be caused by pile driving at distances of more than 30m.

A specific test to measure dynamic strains in brickwork induced by pile driving is also reported. Despite severe vibration, no damage occurred.

1. INTRODUCTION

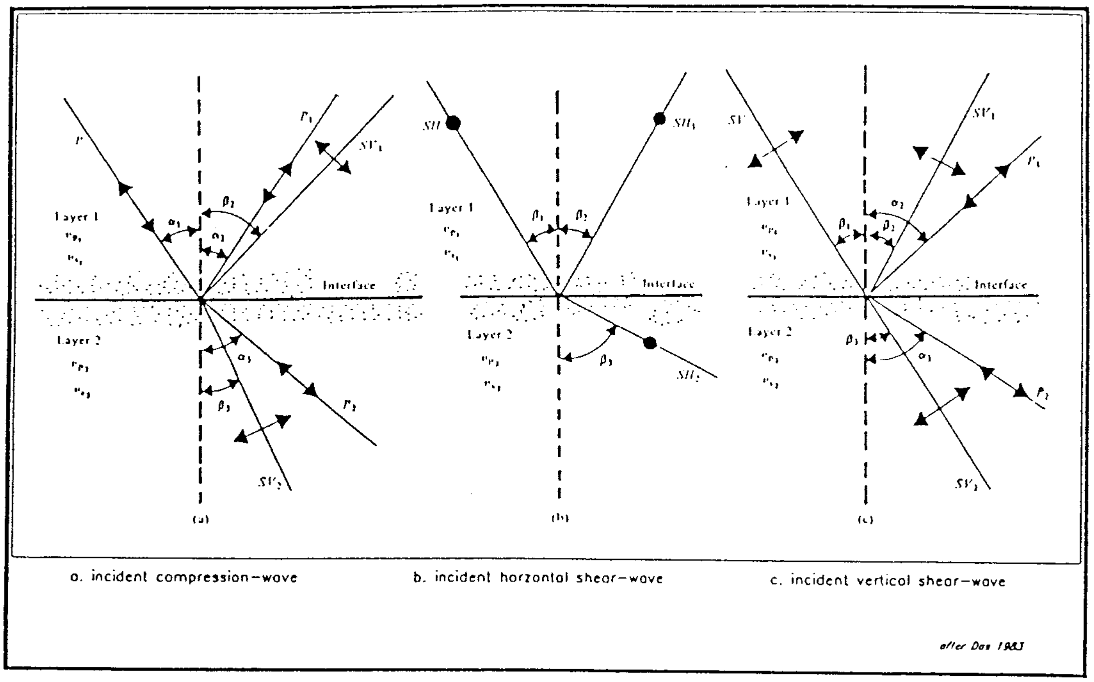
When an impact hammer strikes the head of a pile, during the driving operation, a compressive wave travels down the pile to the toe (Smith 1960, Goble & Rausch, 1976). A large proportion of the input energy at the head of the pile is dissipated by advancing the pile into the ground and achieving a 'set', some energy is reflected back up the pile and some energy is transmitted into the soil which expands outwards over a spherical wave front primarily as a 'P' wave. A second possible source of ground vibrations is the downward motion of the pile shaft, causing vertically polarised shear waves to propagate outwards in a near-cylindrical wave front. A third source of vibration arises because the impact at the pile head causes some transient lateral deformation of the pile; this may be 'whip' of the upstand length of pile in a cantilever mode, or if the pile head is restrained in position by a leader or head frame, then a bowing deformation may occur. In either case, a surface wave may be set up which propagates outwards from the pile shaft around a circumferentially expanding wave front. These wave fronts are shown schematically in Figure 1. (See also Attewell & Farmer, 1973). A description of surface waves should include consideration of wave reflection and refraction at ground surface, see Figure 2 and Pekeris (1957) and Das (1983).

Whilst these descriptions offer a useful introduction to the problem, experience shows that a purely analytical approach to the problem is inappropriate. Firstly, the zone of interest in the ground surface vibrations, typically within 20m or so of the pile, implies that the various wave trains arrive at any measuring device in a superimposed group, rather than separated into discrete parcels of energy, as occurs in seismic work. Also, the imprecision of the pile driving equipment and the variability of the ground inevitably cause resultant vibrations of a complex nature.



after Attewell & Farmer 1973

Figure 1. Wave mechanisms caused by piling



a. incident compression-wave

b. incident horzontal shear-wave

c. incident vertical shear-wave

after Das 1983

Figure 2. Reflection and refraction of incident body waves

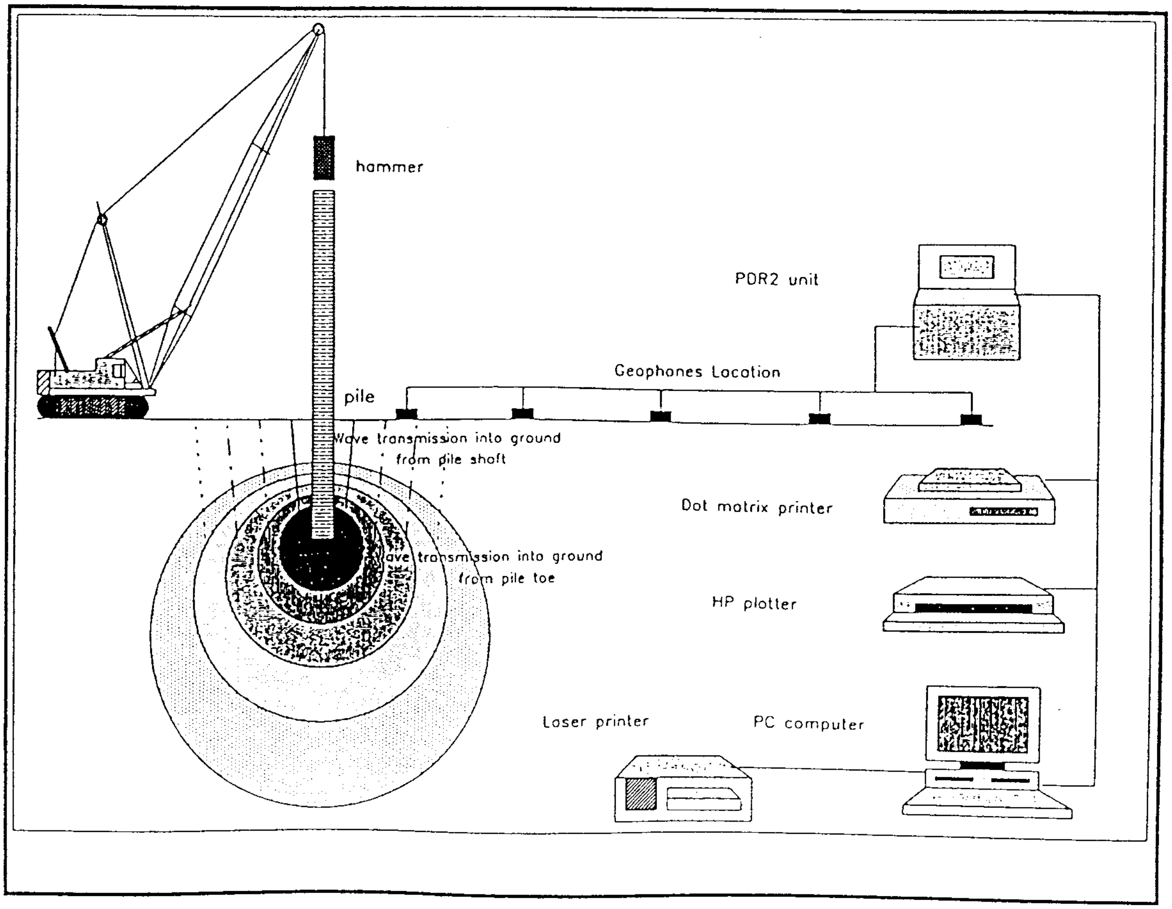


Figure 3. Schematic of vibration measuring system

Consequently, an empirical approach has been adopted, in which a large number of site measurements has been taken, using multichannel digital recording equipment to allow simultaneous readings of radial, transverse and vertical components of vibrations at each of five stations at different stand-off distances from the pile. The vibration measurements from the 15 transducers were stored on floppy disc, allowing later detailed processing and analysis.

2. THE MEASURING AND RECORDING SYSTEM

The equipment used for measurement and recording of ground surface vibrations consisted of 15 geophones (velocity transducers), connected to a portable digital recorder/processor (PDR2). Each geophone produced an electrical voltage signal proportional to transient particle velocity, and required no excitation voltage, being of the coil/permanent magnet type of device. Calibration of each instrument was performed by back-to-back dynamic test using an accurate accelerometer. The PDR2 unit comprised four A/D convertors, each with multiplexor, and 2 Mbytes of RAM, together with keyboard, twin disc drives and back lit screen, housed in a wooden case. The electronics were powered by a portable generator. The system is shown schematically in Figure 3, and its specification, performance and operation are described in detail by Selby & Swift (1989) and by Uromeihy (1990).

The postprocessing facilities included time-based vector resolution of the R,T and V components at any one station, frequency analysis of any signal by F.F.T. (Fast Fourier Transform), integration or differentiation of particle velocity traces to give displacements or accelerations, printing of peak particle velocities, and colour plotting of one or more vibration records.

The procedure for measurement of vibrations on a site was to spike into the ground the sets of geophones at say 2, 4, 8, 12 and 20m horizontal distances from the pile to be driven, and connect the cables to the PDR2. The data capture program was loaded into PDR2, and the correct operation of the geophones was checked. Data capture parameters were then entered, e.g. trigger channels and trigger levels, rate of sampling and duration of record (including pretrigger data capture). The RAM was then cleared ready for data capture, and files of vibration data were recorded on demand, with autotriggering. The files were transferred to floppy disc for storage, and careful manual records were made of file codes, hammer type and operation, pile section and toe depth.

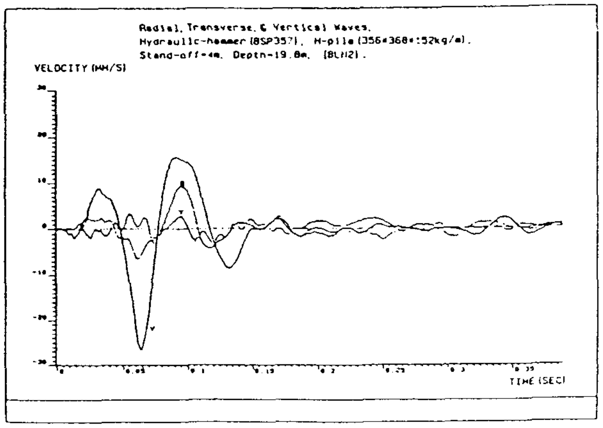


Figure 4. Velocity traces caused by a drop hammer

Typical example traces of ground vibrations recorded during pile driving by impact hammer and by vibrodriver are shown in Figures 4 and 5. Sites were visited throughout England and Scotland in order to record vibrations caused by a range of hammers driving either sheet or bearing piles into various soils and to different depths of penetration.

A few examples of vibration attenuation plotted as a function of horizontal distance from the pile, Figures 6, 7, and 8, show clearly that the decay of time-based vector resultant, and of the radial, transverse and vertical (R,T,V) components, is non-monotonic; indeed peak values may even be observed, often at some 10m from the pile.

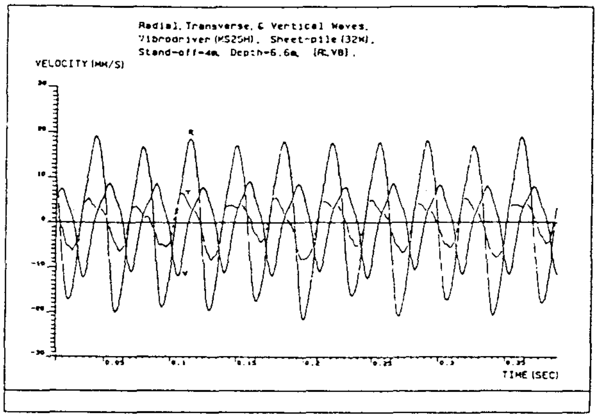


Figure 5. Velocity traces caused by a vibrodriver

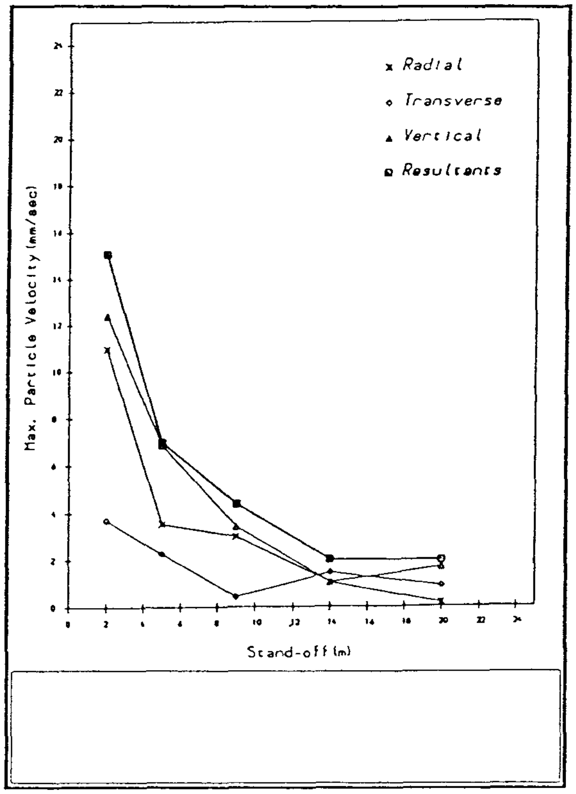


Figure 6. Attenuation of vibrations with distance - vibrodriver

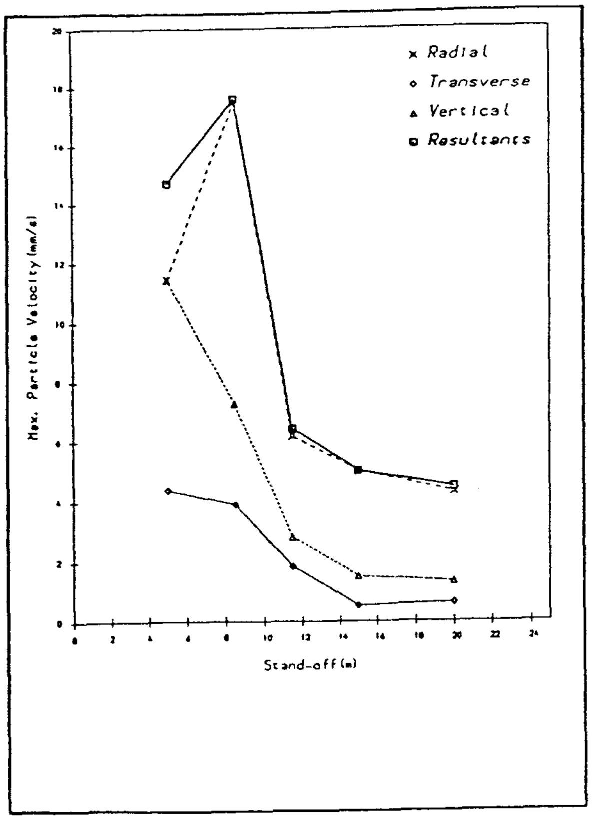


Figure 7. Attenutation of vibrations – diesel hammer

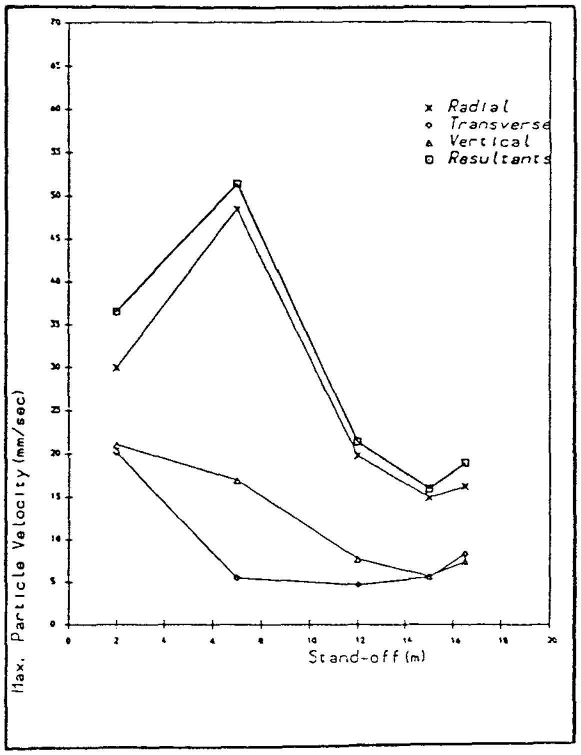


Figure 8. Attenuation of vibrations – drop hammer

Consequently, rather than fit regression lines of peak particle velocity against (√W/r), see Attewell and Farmer (1973), a database approach was adopted. Each record of vibrations at 2, 4, 8, 12 and 20m from the pile was characterised by cubic equations for R, T, V and resolved components of velocity. The structure of the database was such that rapid recall of the recorded particle velocities (or derived accelerations or displacements) was possible for various groups of records. In response to categorising commands (e.g. type of hammer, type of pile, soil parameters etc), the database would be scanned, and appropriate records would be selected. Some 120 sets were available in the database. A 'loose' definition, on one parameter only (e.g. sheet piles), would result in a large number (say 50) of selected records for recall and display. A 'tight' definition on several parameters (e.g. vibrodriver, steel H piles, dense sandy gravel, toe depth 5-10m), would recall a small number of comparable records (say 5) or might possibly even result in zero recall, signifying a total mismatch.

The database was mounted on an R.M. Nimbus p.c. with enhanced memory, using the Smartware 2 system, linked to a laser printer. In this format it was easy to recall measured levels of vibration from a site with piles and drivers similar to a proposed scheme, from which to deduce probable vibration levels for a proposed piling activity. An expert system for vibration estimation has been completed recently, Oliver (1991).

The expert system was required to respond to queries such as 'what vibrations will be caused by driving Pile X into soil type Y?' Thus, for given pile and soil, the system was designed to select hammers (drop, diesel, air and vibrodriver) of just sufficient energy rating to drive the defined pile, and then to estimate vibrations for all four cases.

3. THE SENSITIVITY OF PEOPLE TO VIBRATION

Many authors have observed that the human frame is very sensitive to vibrations in the 1 to 80Hz frequency range. The various observations are usefully summarised by the Reiher-Meister scale, which is indicated graphically in Figure 9, with ppv's superimposed. It shows that initial perception can be as low as 0.3mm/s, while annoyance occurs at about 3mm/s. Many of the records on the database were taken for the range of 2m to 20m, and it was commonplace to observe values of 5mm/s at 20m from the pile. One of the few records of vibrations at up to 37m from the pile, Table 1, showed vibrations around the 'annoying' threshold. More typically, however, vibrations had reduced to 3mm/s by 15 to 20m from the pile.

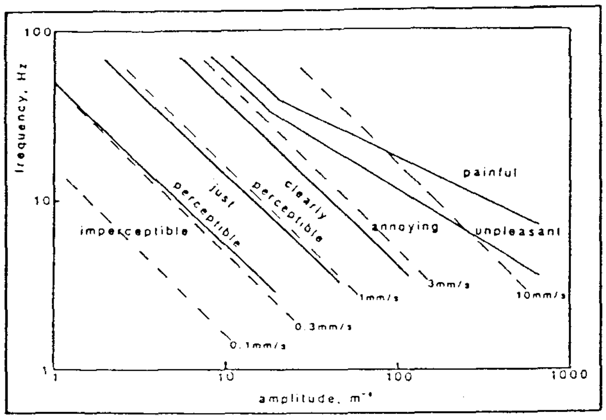


Figure 9. Rieher-Meister scale, with imposed velocities

Table 1. Example vibrations, drop hammer, H-pile

Disc no	Date	File name
PDR2-N	28.06.1988	BLN
Pile		
Type	Dimensions	Length
H-pile	356 × 368 × 152kg/m	21m
Hammer		
Weight	Model	Drop height
5000kg	Hydraulic-hammer (BSP357)	800mm

		Peak Particle Velocity Measurements (mm.s^{-1})					
File no.	Depth (m)	Geophone-set Stand-off	A 4m	B 8m	D 17m	E 27m	C 37m
B	-	Radial	10.08	10.79	13.83	4.24	3.26
L		Transverse	4.55	2.29	2.32	2.95	0.94
N	19.5	Vertical	25.92	9.34	10.95	2.73	1.21
1		Resultant	26.37	12.13	14.99	4.67	3.46
B		Radial	9.36	11.15	14.43	4.69	3.40
L		Transverse	3.53	2.57	2.68	2.36	1.02
N	19.8	Vertical	26.80	8.26	11.06	2.55	1.29
2		Resultant	27.47	12.13	15.47	4.97	3.62
B		Radial	8.19	12.34	15.31	4.51	2.89
L		Transverse	3.44	2.48	2.77	2.53	1.14
N	20.0	Vertical	24.06	8.26	11.46	2.27	1.26
3		Resultant	24.67	12.77	16.41	4.62	3.04
B		Radial	6.30	12.61	16.23	5.68	2.70
L		Transverse	3.99	2.67	3.30	2.56	1.06
N	21.4	Vertical	24.45	8.71	11.46	2.09	1.47
4		Resultant	24.48	12.77	17.31	5.96	2.92

Levels of vibration at various distances from the pile are functions primarily of hammer type (impact or vibrodriver), hammer energy per blow or per cycle, pile size, and to a lesser extent soil conditions. Reference to the database will produce records of vibrations measured under piling conditions similar to a proposed construction, and from these cases, or by accessing the expert system, the risk of levels of disturbance can be deduced.

4. TOLERANCE OF BUILDINGS TO GROUND VIBRATIONS

everal national codes or standards around the orld make recommendations of limits of acceptable ibrations incident upon buildings, and some examples are shown in Figure 10, as a function of frequency, for domestic buildings. It is interesting to note that the German and Swiss codes allow larger ppv's with higher frequency, and that some codes including the draft British Standard 5228 Pt 4 (1990) propose a higher limit for intermittent vibrations (e.g. 10mm/s) than for continuous vibrations (say 5mm/s). Also of interest is the wide difference between the German and Australian codes. A detailed study has been undertaken by Steffens (1985).

5. FIELD TESTING OF BRICKWORK WALLS

Against this background, a field test was undertaken in which a steel H section pile was driven by drop hammer or by vibrodriver close to each of four brickwork corner walls. Each wall unit was instrumented with electrical resistance strain gauges, glass tell-tales and with studs for a demountable mechanical gauge. The site for this test comprised 2m of soft silty sandy clay, a 2m layer of dense gravel and sand, then deep deposits of very dense light grey uniform fine sand.

Details of the test procedure were outlined by Selby (1989). A schematic view is presented in Figure 11. Basically, a 12m long 305x305 @ 89kg/m pile was set up at 15m away from a brick wall unit (2m and 1.5m long, 1.5m high), and driven by 3.2t drop hammer falling through 1m, or by a PTC 13HF vibrodriver operating at 28Hz. Ground vibrations were measured by geophones, and dynamic strains in the walls by ersg's. The pile was repeatedly extracted and redriven closer to the wall, at 10m, 5m, 2m and 0.5m. Severe ground vibrations of up to 70mm/s were recorded, and coincident transient strains of up to 100 x 10^{-6} were observed, Figure 12. Despite such high transient strains, the walls sustained no damage, as was demonstrated by the

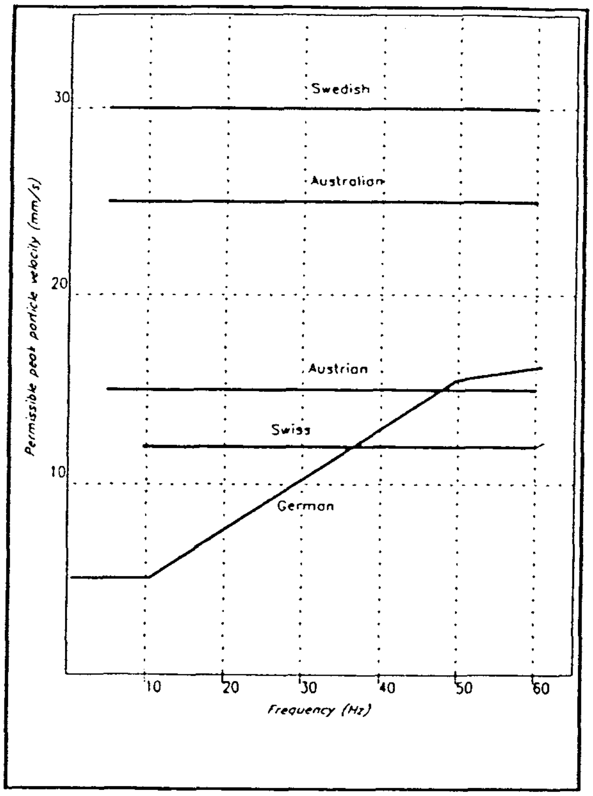


Figure 10. Some national standards for limiting peak particle velocities for domestic brick buildings

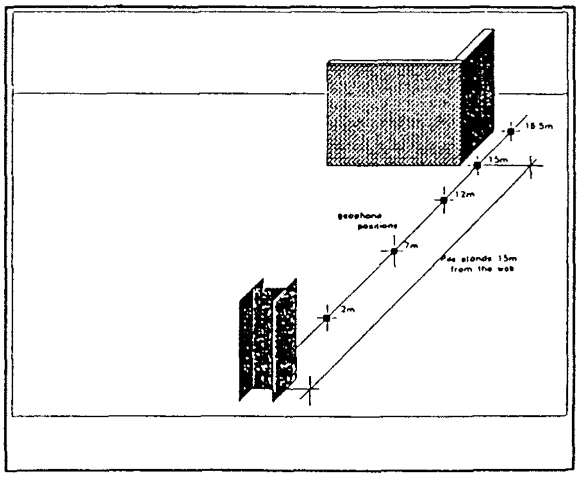


Figure 11. Schematic of pile driving near a brick corner wall

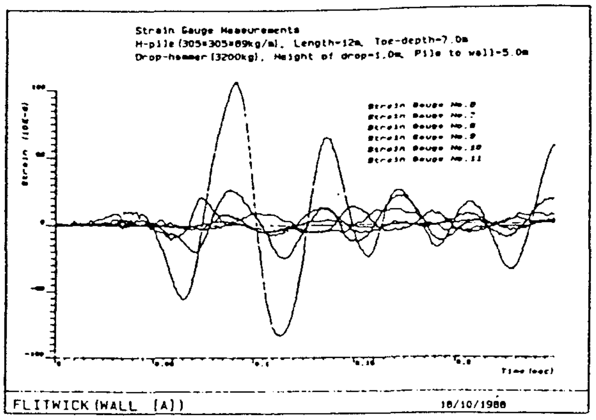


Figure 12. Dynamic strains in a brick wall

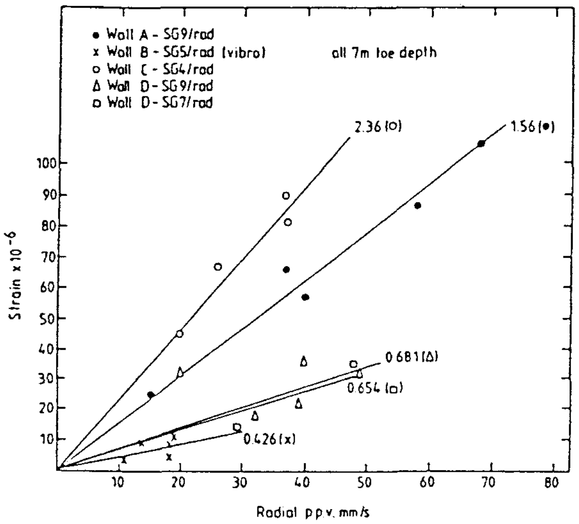


Figure 13. Dynamic wall strains as functions of radial ground vibration

integrity of the glass slips, and by the negligible changes in demountable gauge readings.

It was found that a reasonably linear relation could be derived between the peak radial vibration incident upon the wall, and the maximum transient strain in the wall, (see Figure 13). Note that Wall C was of half-brick construction with dpc and some open joints, walls A and B were of standard half brick construction, and Wall D was 'full-brick' thickness. It should also be noted that the walls responded partly in rigid body mode, being of small size with respect to the wavelength of the incident vibrations. Structures of larger dimensions would be expected to show larger strains in response to a given incident vibration.

6. CONCLUSIONS

Ground vibrations caused by pile driving comprise complex radial, transverse and vertical components at the adjacent ground surface. A large number of multichannel simultaneous recordings have been made on sites in the United Kingdom. Because of the complexity of the records, and to allow further post process analyses, the measured vibration sets were stored in a database. This device allowed rapid recall of measured vibrations for comparison with proposed piling activities.

Typical records show that annoyance to a neighbour will usually be caused when piling takes place within some 15m of his property. By reference to current national codes or standards, it appears that it might be unwise to pile sufficiently close to domestic building such that vibrations exceed some 10mm/s, if minor damage cannot be tolerated. This will often be caused by piling within say 5 to 10m from the building.

In a major field test, the peak strains induced into small brickwork walls by piling were shown to be proportional to the incident radial components of vibration. The steepest gradient of 2.3 x 10^{-6} strain per 1mm/s was recorded when a half brick wall with some open joints was subjected to adjacent piling by drop hammer, while the high frequency vibrodriver caused the least severe relation of 0.43 x 10^{-6} strain per 1mm/s. The response of a large brick structure might be more severe if its major dimension were closer to the wavelength of the vibration. Notwithstanding this, the tests showed the brickwork to have an impressive tolerance to dynamic strains of over 100 x 10^{-6}, without any damage; the results must therefore enhance confidence in the ability of brickwork to withstand, without damage, significant dynamic strain caused by pile driving.

Further work into the dynamic strain capacity of brickwork and of plaster is desirable. Tests on a full scale domestic brickwork house in response to piling, with measurement of dynamic strains would be of value in clarifying risk to structures from pile vibrations.

7. ACKNOWLEDGEMENTS

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